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Team 14: Anti-Piracy and Terror Reduction: Simulating Pirate Behavior to Exploit Environmental Information

Esher, Leslie

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Simulating Pirate Behavior to Exploit Environmental Information

TEAM 14 MEMBERS

Leslie Esher, LT USN
Stacey Hall, LT USN
Jim Hansen, PhD
Eva Regnier, PhD
Paul Sanchez, PhD
Dashi Singham, PhD Candidate

Problem

Due to the increase in pirate activity off the coast of Somalia, the United States military and the combined forces of the world's navies are partnering together to defeat these violent extremists. Piracy has threatened maritime safety and cost commercial shipping billions of dollars paid in ransom monies. The Gulf of Aden and the Horn of Africa that were once safe to transit are no longer, and for this reason, President Obama has issued an executive order to defeat terrorism in the form of piracy. The Commander of the U.S. Naval Forces Central Command (CENTCOM), U.S. Fifth Fleet, Combined Maritime Forces (CMF), is responsible for the safety, stability, peace, and vital interests of the United States for 2.5 million square miles of water. For the contents of this paper, the region of geographical concentration has been on the area that has been the most prevalent to pirate attacks, Somalia. Combined Task Force 151 (CTF 151) is a multi-national task force that is response for 1.1 million square miles of water in the Gulf of Aden and off the coast of Somalia.

Pirates in this area generally operate from small boats (skiffs) that have limited survivability at sea in severe weather conditions; this paper will refer to these conditions as METOC, (Meteorology and Oceanography) conditions. High sea state and/or wind speeds make it difficult or nearly impossible for pirates to attempt to board commercial vessels. The analysis of this paper is to provide insight into what parameters are most influential in contributing to and limiting pirate behavior.

In response to the piracy problem, the U.S. Naval Oceanographic Office (NAVOCEANO) at Stennis Space Center has been providing a forecasting product, called the Piracy Performance Surface (PPS) that uses forecasts of winds and seas to map the locations that are most conducive to pirate activity, and incorporates information on confirmed pirate activity in the form of an attack, an attempted attack, or suspicious activity. The existing product was developed rapidly to provide support to the operators. NAVOCEANO is working to improve the model of the relationship between METOC and pirate activity, and to improve the way the pirate threat is updated when confirmed piracy activity is observed.

The overarching research question is: How can the N2/N6 (Director for Information dominance that comprises information, intelligence, command, and control) contribute decision-critical information to the operators who are protecting commercial shipping traffic.

By September 2010, a new simulation-based engine will be implemented to produce the PPSNext. The simulation is based on a model of pirate behavior (hereafter, CONOPS, Concept of Operations), combined with forecasts for METOC conditions and intelligence on certain parameters of pirate behavior, such as whether they operate from land or sea bases (mother ships) and the number and locations of these bases.

The goal of Team 14 was to provide insight on which parameters describing pirate CONOPS were the most important drivers of the map reflecting relative pirate threat and which have the strongest interaction with METOC variables. These results would indicate which factors in pirate CONOPS are most important to include in the model and which parameters should receive most intelligence resources.

Simulated Pirates and Environment

In the model of pirate CONOPS, the basic strategy is to depart from a base – either a land-based camp or a sea-based mother ship – typically a Boston Whaler that has longer longevity and life expectancy at sea, with a handful of pirates with a few days' supplies. The skiff motors to its pre-determined location (latitude and longitude). As illustrated in Figure 1, the skiff then drifts with the winds and currents

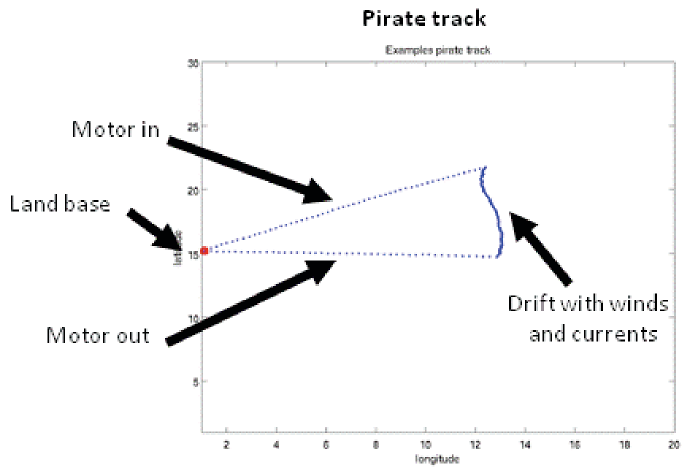

Figure 1: Example of a pirate skiff trajectory

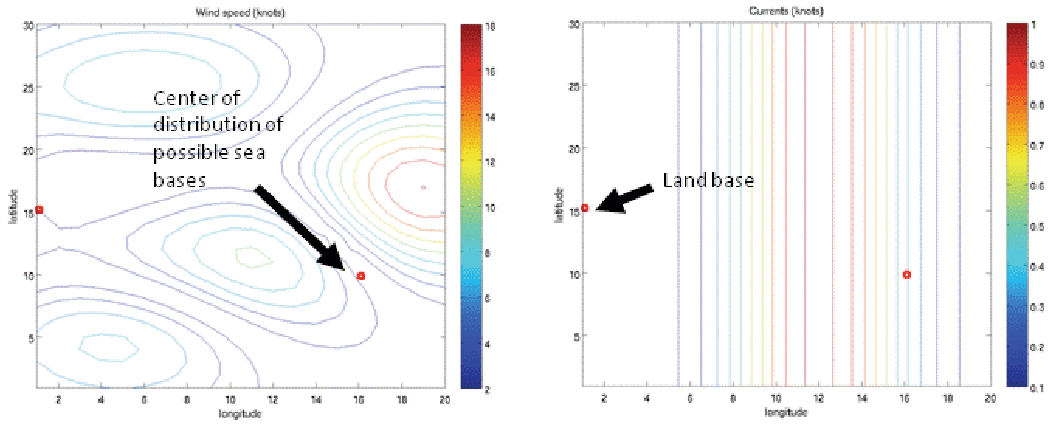

Figure 2: Simulated winds and currents.

until the pirates run out of supplies, at which point the skiff motors back to its land or sea base.

Winds, waves and currents affect the pirates. In their drift phase, their motion is determined by currents and winds. In addition, one of the factors whose impact we are evaluating is whether pirates use weather forecast knowledge to plan and implement an attack. In the current implementation, if the pirates have forecast knowledge, is it assumed that their information is “perfect”. If they have forecast knowledge, they do not go to locations with unacceptable weather-as determined by wind and wave thresholds. If they do not have forecast knowledge and encounter unacceptable weather, they return to their base location.

In its operational implementation, the METOC conditions will be the result of a coupled atmospheric-oceanic model. In the version used experimentally for IDFW-20, notional winds, seas, and currents were used (shown in Figure 2) that changed over the course of the 72-hour simulation, but otherwise did not vary as a function of simulation trial. The pirates operate in a 20×30-cell grid, with each cell 10 km on a side.

Output Statistics

Considerations

Perhaps the biggest challenge this group faced was how to summarize the simulation’s output. Although there is a limited database of historical pirate attacks, it has not been possible so far to recreate the METOC conditions corresponding to the period of known pirate activity against which to verify the model. Therefore, for any experiments conducted during the IDFW, there is no ground truth against which to compare results. In addition, even if we consider only the relative density of pirate activity across the simulated area and summarize pirate activity in 12-hour periods, each simulation produces a pirate density in each of 600 cells at each of six time periods (See Figure 3). Each simulation must be summarized and compared usefully with the results for other design points, to identify the variables that are most influential and most related with METOC conditions.

As described below, we undertook an experiment with 33 design points (simulations), and therefore 528 pairs whose similarity or difference might be measured. Within each simulation, differences across the six time periods would reflect sensitivity to METOC conditions (which changed over

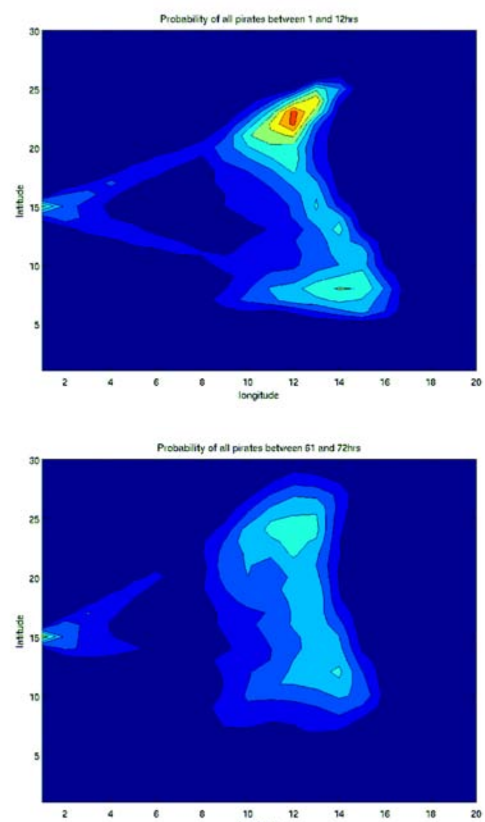

Figure 3: Sample PPSNext simulation output.

the course of the 72 simulated hours) and interactions with METOC conditions. Comparing the six pirate density plots would result in 15 pairwise comparisons.

Potential summary statistics

We considered summary statistics for comparing two maps of pirate density (whether they were from the same time period, and different design points, or the same design point, but different time periods). The following Y-variables were used in our experiment:

- The maximum root mean square cell-by-cell difference (RMSE) between each design point and all other design points. RMSE especially penalizes large errors.
- The cell-wise maximum difference (MaxDiff) in pirate density between each design point and all other design points
- For each trial, the largest RMSE between a 12hr pirate density and the 72-hour averaged pirate density map (this response variable is called ΔRMSE, and analogous measures are ΔMaxDiff and Δ50th prctile)
- The mean across time-periods of the area that bounds 50% of the pirate density (50th prctile).
- Same as each of the above, but for smoothed distributions (indicated by S-prefix).

Other summary statistics that we considered, and which might be applicable in future work include:

- Cell-by-cell differences in mean relative entropy.
- Location: minimum distance between two modes (or sum of minimum 2 or 3 distances).
- Decision-related
  - How much of the total pirate density can be captured within miles of optimally deployed search assets?
  - How big would circular covering disk have to be to capture 75% of the pirate density?
  - Sum of differences over larger ("coarse-grained") cells that might be defined according to the size of an area searchable by Task Force 151 assets within a given time?
- Other:
  - Fourier transform
  - Max eigenvector

Experimental Design

Because the current implementation of the simulation is in Matlab, and therefore we expected each trial to take an hour or two to run, we knew we would be limited in the number of design points. To capture the effects of all variables and interactions among them, we used a Nearly Orthogonal Latin Hypercube (NOLH) design (Cioppa & Lucas, 2007), downloaded from SEED center website. We restricted ourselves to experiment with eleven input variables (X-variables), which allowed us to use an experimental design with 33 design points, which we anticipated was few enough that we could complete the runs overnight. The variables and their maximum and minimum values are shown in Table 1 below.

Variable	Minimum	Maximum
Simulated pirates per day	200	1200
Mission length (hours), *Length*	72	120
Pirate groups	3	7
Total number of land and sea bases*	3	7
Proportion of bases that are sea bases*	0.25	0.5
Known base locations (Yes/No)	No	Yes
Transit speed (kts), *Speed*	8	12
Pirates' wind threshold (kts, *Wind*	10	20
Pirates' wave threshold (ft),*Wave*	3	10
Probability that pirates use forecasts	0	1
Wind drift factor, *Drift*	0.1	0.75
*Used to calculate number of land bases (*Camps*) and sea bases *(Sea Bases)*		

Table 1: Input variables (X) used in the experiment

RMSE	S-RMSE	MaxDiff	ΔRMSE	S-ΔRMSE	ΔMaxDiff	ΔS-MaxDiff	50th-prctile	S-50th prctile
0.77	0.68	0.38	0.55	0.77	0.66	0.84	0.73	0.71
Length × *Wind*	*Length*	*Speed* × *Drift*	*Wind*	*Wave*	*Wave*	*Wave*	*Length*	*Length*
Wave^2	*Wind*	*Drift*	*Wave*	*Wind*	*Wind*	*Wave*^{2}	*Wind*	*Wind*
Wave	*Wave*	*Speed*		*Camps* × *Wave*	*Sea Bases*	*Camps*	*Sea Bases*	*Speed*
Drift	*Length* × *Wind*			*Camps*	*Sea Bases* × *Wave*	*Wind*	*Speed*	*Sea Bases*
Wind	*Wave*^{2}					*Camps* × *Wind*	*Sea Bases* × *Speed*	
Camps × *Drift*								
Camps								
Length								

Table 2: For each output measure, adjusted R2 and input variables included in the fitted regression model, ordered from most to least influential.

Results

For each Y-variable, we used JMP statistical software to fit a regression model to a set of 75 potential predictors, i.e. the variables shown in Table 1, their squares, and all first-order (pairwise) interaction terms. JMP performed stepwise regression, allowing variables to enter and leave the model based on their significance (p-value).

Table 2 shows the X-variables that were included in the model, as well as the R2 and adjusted R2 for each model. Wave threshold and wind threshold proved to be the most significant in the current Matlab implementation of the PPSNext model, and at least one of these two variables appeared in the model for every Y-variable.

The absence of some X-variables is very interesting. For example, these results seem to indicate that it is not important for intelligence to learn whether pirates can acquire and use METOC forecasts, nor would it change the PPSNext if they acquired that capability.

The Δ-prefixed Y-variables measure differences within a single simulation (design point) over the 72-hour simulated time period, rather than differences relative to the other design points. Therefore, the X-variables that are most related to the Δ Y-variables can be interpreted as those that have the largest interaction with METOC conditions. Both wind and wave thresholds appear in the model for every Δ Y-variable, indicating that (not unexpectedly) wind and wave thresholds interact strongly with METOC conditions in determining the spatial distribution of pirate activity. The wind drift factor and mission length do not appear in any of these models, however, indicating that they do not interact strongly with METOC conditions.

X-variables that might be estimated using intelligence also appear to drive the results, in particular mission length. The interaction between mission length and wind threshold in two of the models is interesting. The number of sea bases or camps – which are highly related, as the number of sea bases is a fraction of the total number of bases – appear in many of the models, indicating that it would be valuable to have good estimates of the number of bases.

The results do not provide clear guidance as to which of the output measures are more useful. In addition, smoothing does not have a consistent effect on the significance of the results. For some measures, the smoothed output model achieves greater R2 than the raw value and for some measures the opposite. The smoothed MaxDiff did not produce any X-variables that were significant at least at the 0.01 level, and therefore its model is not shown in Table 2.

Future Work

Near-term future work on this project (in the next year) includes running similar experiments using the operational code, which will include environmental and navigational conditions for specific, real area of operations, in particular the area off the HOA plus the Gulf of Aden. We will seek to confirm the qualitative results of the experiments conducted during IDFW-20, to identify which aspects of pirate CONOPS are most critical in interaction with METOC conditions and METOC uncertainty.

Another major component of future work in the next year is the possibility of building an agent-based model that will be able to represent other factors that we know to be important to the problem of detecting and protecting against the pirate threat. In particular, we would like to add agents that represent commercial shipping, the searchers and neutral vessels. We spent some of our time researching environments for implementing an agent-based piracy model and the key features that we would like to see included.

Donna Middleton (Northrop Grumman) gave us a demonstration of Pythagoras, including a simulation she created to capture the effects of currents and waves. Pythagoras has the flexibility to model pirate behaviors such as seasickness and incorporate behavioral habits where pirates run out of cot, food, or water so they return to their origin at different times for a single time step simulation. Another great asset for agent based modeling is the ability to run a multitude of simulations quickly. The downfall of using this agent-based model is the inability to model METOC as fluid dynamics since weather conditions change with each time step. METOC would be static while the agents would be dynamic. Although this feature is not represented in the current pirate simulation, it would be nice to allow agents to have imperfect information about METOC conditions, representing a forecast.

Mary McDonald also visited our team to discuss the applicability of MANA to this problem. We took some time to analyze the pros and cons between each agent-based model. MANA did not have the model flexibility that we so desired with modeling pirate agents and it too has the inability to model changing METOC conditions. Abel (2009) used MANA productively to model frigate defense effectiveness against pirate activity because MANA enabled him to model quadrant dimensionality of the frigate in the form of port, starboard, fore, and aft.

References

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